Determination of optimum welding parameters in connecting high alloyed X53CrMnNiN219 and X45CrSi93 steels by friction welding

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Abstract. In this study, different welding parameters were applied to two different steels with high alloys and mechanical and metallographical investigations are performed. Thus, the optimum welding parameters were determined for these materials and working conditions. 12-30 diameter steel bars made up of 1-4871 (X53CrMnNiN219) and 1-4718 (X45CrSi93) steel were used as experimental material. The material loss increased with increase in friction and rotating pressure. No fracture at the welding region was observed and the highest fracture energy was identified in B5 group. Based on micro hardness investigation; the hardness profile reached its minimum value at the welding region.

Keywords. Friction welding; welding parameters; microstructure.

1. Introduction

Joining has increasingly been used in the material technology because materials having different mechanical properties need to be efficiently joined to increase its performance. The most suitable method of joining two different alloyed steel is welding (Anık 1983). After welding process, the properties of welding zone naturally become different from the properties of alloyed steels and this difference may cause some problems. Using melting welding methods, among many kinds of welding methods, has also increased these problems (Yılmaz 1993). Phase diagrams and properties of joining materials are important factors in determining welding properties (Bargel and Schulze 1988). Some problems also arise because the materials to be joined are different alloys and some additional components are needed to effectively join them. Many different zones appear at connecting region depending on composition and material properties (Yılmaz 1993). Remaining deposits of the melting welding methods, welding porosity faults are the important disadvantages of these methods and they reduce the strength of welding. Therefore, solid state welding methods are more suitable since melting welding faults do not significantly occur there (Tülbentçi and Yılmaz 1989).

Vill (1962) has conducted a study to determine optimum conditions of friction welding parameters. He has

determined that friction pressure coming from welding parameters is of great importance and it can be fixed in a wide surface depending on the materials used. Moreover, Tyleote determined that friction pressure affects the heat of surface and supplies the required moment. He also reported that forging pressure and cycling number are the most important parameters (Tylecote 1968). It can be said that low welding periods have supplied the best welding zone in low carbon steels, which requires applying forging pressure of one second as well as applying high forging pressure (Duffin and Crossland 1971). Low welding periods and high forging pressure values form a thinner granular structure for low carbon steels (Voinov 1972). In notch impact test results, better mechanical properties have been obtained on high cycling numbers between 1200 and 4200 rpm according to other constant parameters (Welding Handbook 1980). A friction pressure of 30–65 MPa, and a forging pressure of 75–140 MPa must be applied for low carbon steels and a friction pressure of 70–210 MPa and a forging pressure of 100–420 MPa for medium carbon steels (Welding Handbook 1980).

In another study, Ishibashi *et al* (1983) have found that forging pressure value must be applied twice as much as that of friction pressure for stainless steels. In a study on tool steels, it has been advised that the welding temperature and, in turn, friction pressure should be high enough so that no faults on welding zones will occur (Tanicheva *et al* 1989). Initially, conventional arc welding and then solid state joining methods were applied on welding processes of stainless steels (Gooch *et al* 1996). Today, friction welding is one of the solid state joining

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techniques used widely for stainless steels. Bol'shokov (1972) reported that friction welding on vacuum condition improved mechanical properties of joined materials.

Main advantages of friction welding are high materials saving, low production time and possibility of welding of dissimilar metals or alloys (Şahin 2004). Nowadays, valves, bandix gears, axle shafts, gearshaft components, turbocharged fan shafts, fork-shaft connections etc. in automotive industry are manufactured by the consolidation of alloy steel and normal carbon steel using friction welding process (Chalmers 2001). The most effective parameters in friction welding process are friction time, friction pressure, upset time, upset pressure, rotation amount and the characteristic features of the welded material (Alvise *et al* 2002; Bayındır and Ateş 2007).

With the technological development in the valve manufacturing industry, the exhaust valves of normal and diesel engines are manufactured from two different types of steels. The 'handling' parts of exhaust valves are manufactured from 1-4718 (X45CrSi93) steel which is tough, ductile and resistant against wearing due to friction while the 'head' parts are manufactured from 1-4871 (X53CrMnNiN219) steel which shows a very good resistance against oxidation, hot corrosion caused by lead oxide and other burning products. Today, this steel couple is joined by friction welding (Uzku 1999). Friction welding is one of the methods with a large share among the other conventional welding methods. The most important parameters in friction welding are friction time, friction pressure, forging time, forging pressure and rotational speed (Uzku 1999; Şahin and Akata 2003).

Welding faults in the valve manufacturing may occur due to thermal and mechanical stresses. Therefore, optimizing welding parameters are essential. The determination of optimum welding parameters and joining zones will minimize these faults on welded parts (Uzku 1999). In this study, optimum welding parameters of high alloyed X53CrMnNiN219 and X45CrSi93 steels used in

automotive industry were determined by friction welding and by doing tensile, notch impact, metallography and microhardness tests.

2. Experimental

X53CrMnNiN219 (1-4871) and X45CrSi93 (1-4718) high alloyed steels were used in the experiments. Standards of materials are shown in table 1, chemical composition of materials in tables 2–3, mechanical properties of materials in table 4, standard measurements of welded tensile samples in table 5, and values of applied welding parameters are shown in table 6.

Rotation number (n) and forging time (t_2) were kept constant and friction time (t_1), friction pressure (P_1), and forging pressure (P_2) had different levels. Constant parameters and values for 12.3 mm diameter of specimen were determined as follows: experimental bar diameter is 12.3 mm (H9), rotation number of spining parts is 3000 rpm during welding process, rotation number of spining parts is 1500 rpm during machining process, friction contact time is 0.4 s, brake delaying time is 0.1 s, forging delaying time is 0.8 s, forging time is 2 s, friction pressure rising time is 1 s, forging pressure rising time is 1 s, and waiting time at the end of forging time is 1 s. The levels of studied parameters were as follows: friction time (2.70, 3.70, or 4.70 s), friction pressure (138, 207, or 276), and forging pressure (345, 414, or 480 MPa). The specimens subjected to friction pressure of 138 MPa is called group A, of 207 MPa is called group B, of 276 MPa is called group C.

Tensile test of TS-138 (Turkish Standard), one of the mechanical tests, was carried out by 5 kN capacity universal 1114 model INSTRON type. Tensile velocity was taken as 1 mm/min at tensile test. Notch impact test was carried out at 25°C depending on TS-269. Standart notch was opened on welding line. Suitable standard measurements were applied on specimen.

Table 1. Standards of materials.

Material	W. Nr	AF NORM	BS	EURO NORM
X53CrMnNiN219	14871	Z52CMN21-09	~ 349S52	X53CrMnNiN219
X45CrSi93	14718	Z45CS110	~ 401S45	X45CrSi8

Table 2. Chemical composition of 1-4871 material.

Material	Chemical composition (% wt)							
	C	Si	Mn	Cr	Ni	N	P	S
1-4871 (theoretical)	0.48–0.58	≤ 0.30	7–10	20–22	3.25–4.5	0.38–0.5	Max. 0.050	Max. 0.030
1-4871 (analysis)	0.50	0.27	8.19	20.11	3.90	0.4	0.025	0.001

Table 3. Chemical composition of 1-4718 material.

Material	Chemical composition (% wt)					
	C	Si	Mn	Cr	P	S
1-4718 (theoretical)	0.40–0.50	2.70–3.30	≤ 0.80	8–10	Max. 0.040	Max. 0.030
1-4718 (analysis)	0.42	2.73	0.47	8.71	0.017	0.001

Table 4. Mechanical properties of 1-4871 and 1-4718 materials.

Material	Mechanical properties					
	Diameter (mm)	Length (m)	Circularly (mm)	Surface roughness (μm)	Hardness (HRC)	Tensile strength (MPa)
1-4871 (standard)	12.258–12.300	3.5–4.0	Max. 0.03	Max. 0.8	Max. 40	950–1250
1-4871 (test)	12.280–12.290	4.0	0.005–0.02	0.3–0.8	37–40	1120
1-4718 (standard)	12.258–12.300	3.5–4.0	Max. 0.03	Max. 0.8	29–35	950–1125
1-4718 (test)	12.280–12.290	4.0	0.005–0.01	0.6–0.8	29–32	1030

Table 5. Standard measurements of welded tensile samples.

d_0 (mm)	d_1 (mm)	h (mm)	$(l_0 = 10 d_0)$		
			l_0 (mm)	l_v (mm)	l_t (mm)
6	8	25	60	66	125

Table 6. Values of applying welding parameters and determining fracture energy.

Groups	Fracture energy (J)	Parameters		
		P_1 (MPa)	P_2 (MPa)	t_1 (s)
A1	2	138	345	2.70
A2	3.9	138	345	3.70
A3	6.4	138	345	4.70
A4	2.4	138	414	2.70
A5	4.3	138	414	3.70
A6	7.1	138	414	4.70
A7	1.5	138	480	2.70
A8	3.5	138	480	3.70
A9	2.5	138	480	4.70
B1	6.9	207	345	2.70
B2	6.9	207	345	3.70
B3	10.8	207	345	4.70
B4	6.9	207	414	2.70
B5	14.1	207	414	3.70
B6	6.9	207	414	4.70
B7	6.5	207	480	2.70
B8	9	207	480	3.70
B9	6.8	207	480	4.70
C1	1.8	276	345	2.70
C2	4.9	276	345	3.70
C3	0.5	276	345	4.70
C4	5.9	276	414	2.70
C5	4.7	276	414	3.70
C6	6.4	276	414	4.70
C7	1.8	276	480	2.70
C8	1.1	276	480	3.70
C9	4.8	276	480	4.70

The 1-4871 materials were etched for 10 s and 1-4718 materials for 3 s by 5% nital solution on optical tests. These tests were carried on CARL ZEISS JENA type optical microscope at Dokuz Eylül University laboratories (Izmir, Turkey). A 136° pyramide point Vickers type hardness test method was used for microhardness tests. Microhardness tests were carried out at a distance of 10 μm to welding zone and parallel to welding cross-section. On this study 80 g load was used for the tests; however, a load from 25 g to 100 g could be applied on microhardness tester. Microhardness tests were carried out on CARL ZEISS JENA type microhardness tester at Dokuz Eylül University laboratories. SEM tests were carried out by using JEOL JXA-733 type SEM tester at Dokuz Eylül University laboratories (Izmir, Turkey).

3. Results and discussion

3.1 Mechanical properties

When tensile tests results were examined, mechanical properties of group B found were better than those of group A or C. The basic representative property of group B is that friction pressure is 207 MPa. Break-out did not occur in welding zones of B4, B5, and B6. Common determining characteristic of this group is that friction pressure (P_1) and forging pressure (P_2) values were taken as constant, whereas friction time was variable on these groups. Yield and tensile strengths were similar. As a result, it can be seen that friction time is a determining parameter among these three groups. In determining optimum welding parameters, breaking point on tensile bar, the suitability of post-tensioning yield and tensile strength values for acceptable values of materials, and percentage of extent quantity have significance. Fractures

in 1-4871 material occurred out of welding zone in group B5. Yield strength was 854 MPa, and tensile strength was 1081 MPa.

When notch impact tests results are examined, it has been determined that the energy amounts spent to break the samples of group B are more than those of the other two groups and the samples of B5 in group B spent the highest energy amount (table 6).

Based on microhardness results, microhardness values did not increase in group B5 samples, but microhardness values significantly increased 4 mm away from the centre. The microhardness value was 400 HV in outer cross section for 1-4871 materials, while it was 439 HV at the centre. Microhardness was 483 HV at the centre while it was 439 HV at outer cross section for 1-4718 materials. Cooling was the slowest at the centre of materials. Consequently, element diffusion at materials centre takes much longer time. In addition, movement and mechanical orientation were also minimal at the centre due to materials deformation. Therefore, it is determined that the highest microhardness value is at the centre of materials. The variations of microhardness values depending on distance are shown in figures 1–9. The hardness distributions were determined by using optical and scanning electron microscope.

Figure 1. Variation of hardness of A5 sample in welding zone.

Figure 2. Variation of hardness of B5 sample in welding zone.

Length shortening quantities on post-welding and effects of parameters on length shortening are explained by graphics depending on parameter groups in figures 10–12. As seen in figures, variation on length shortenings depending on welding parameters is linear. A significant material loss due to burning occurs in 1-4718 materials on

Figure 3. Variation of hardness of C5 sample in welding zone.

Figure 4. Quantities of total length shortening depend on friction time for vary forging pressure ($P_1 = 207$ MPa).

Figure 5. Quantities of total length shortening depend on friction pressure for vary friction time ($P_2 = 414$ MPa).

friction welding joints. Total material loss reaches the highest values in the parameter groups having the highest friction time. When we consider all these criteria, A9,

Figure 6. Quantities of total length shortening depend on forging pressure for vary friction pressure ($t_1 = 3, 7$ s).

Figure 7. Mechanical orientation of C5 sample in 1.4871 material grains ($\times 90$).

Figure 8. Orientation of microstructure and grain of A8 sample in two materials ($\times 45$).

B3, B5, B6, B8, B9, C4, C7 and C8, parameter groups differ from other groups according to the length shortening quantities. Efficient length shortening quantities cannot be obtained for 2-7 s friction time. By increasing friction pressure and forging pressure values it is determined that there is much more material loss in the groups subjected to 4-7 s friction time. Length shortening quantities could not be obtained at low friction time in group B samples. In the light of these results, group B5 can be considered ideal for length shortening.

In joining A6061 alloy and SUS304 stainless steel by friction welding, it has been observed that high forging pressures affect the joining strength positively and tensile strength of notched samples increases with increasing forging pressure and maximum effectiveness of joining is seen as 87–93% (Ochi *et al* 1996).

In another study, energy absorption of normalized welding joining is rather more than a normalized one, and

Figure 9. Image of B1 sample in welding zone and HAZ ($\times 45$).

Figure 10. Microstructure of distance zone from welding of B5 sample in 1.4718 material ($\times 180$).

energy transition temperature has been determined at about 24°C at normalized welding joining. This temperature is in agreement with temperature on fracture surface. Crack proceeding strength of normalized welding joining is higher than that of a normalized one. Impact bending strength of normalized welding joining is almost the same as hot processed metal (Kato *et al* 1996).

Şahin *et al* (1996) conducted tensile and microhardness tests, heat and SEM studies on welding zone to determine heat affected zone (HAZ) and metalurgical variations on Al-Al, Al-Steel, and steel-steel using different parameters of friction welding. They reported that welding parameters significantly affected yield, tensile and fracture strength and HAZ zone near the Al was wider on Al-steel joinings. Preparation measures of welding joining must be taken as 1–10 mm per welding by considering length shortening during surface preparation in welded joints (Anik 1983).

Ogawa *et al* (1993) reported high material loss in friction welding of S45C steel, so it has to be examined for its economical impact. In this study, low hardness thin grained ferrite, and pearlite layer occurred on HAZ. Slope of hardness distribution on joining zone has been determined to be low at wider region.

Şahin (2005) determined optimum welding parameters as follows: friction time (4 s), friction pressure (110 MPa) and tensile strength (600 MPa) on high-speed steel (HSS-S6) and medium carbon steel (AISI 1040). He determined hardness of welding zone as 700 HV. Şahin (2007) determined that optimum welding parameters as friction time 9 s, friction pressure 60 MPa and tensile strength 800 MPa on stainless steel (AISI 304). He determined hardness of welding zone as 200 HV. In these studies, the tensile strength of the joints increased with increasing friction time and pressure, and it raised to a maximum,

Figure 11. Microstructure of distance zone from welding of B5 sample in 1.4871 material ($\times 450$).

Figure 13. Mechanical orientation and Fe₂C carburs of B5 sample in welding central ($\times 45$).

Figure 12. HAZ image of A5 sample in central ($\times 180$).

Figure 14. Grain flattening and become small of B5 sample from outer 1.4871 material in HAZ ($\times 180$).

but decreased for more friction time and pressure (Şahin 2005, 2007).

Ateş *et al* (2007) determined friction time as 6 s, friction pressure 70 MPa, and tensile strength 850 MPa on MA 956 iron-based superalloy. They determined hardness of welding zone as 700 HV. In this study, tensile strength increased with increasing forging pressure and friction pressure up to a certain value on HAZ.

Özdemir (2005) and Özdemir *et al* (2007) determined that hardness of welding zone as about 1000 HV on AISI 304 and AISI 4340 steel. In these studies, for excellent welding parameters the friction time was held as short as possible, while the rotational speed, friction and forging pressure was chosen as high as possible. Satyanarayana *et al* (2005) determined that hardness of welding zone as about 270 HV and notch tensile strength 690 MPa on AISI 304 and AISI 430 steel. The differences in our

results and those of other previous studies may be attributed to the fact that their materials and welding parameters were different from ours.

Çelik and Ersözlü (2009) determined optimum welding parameters namely rotation speed, friction pressure, friction time, upset pressure and upset time as 3000 rev/min, 81 MPa, 6 s, 162 MPa and 14 s, respectively, in the joining process of AISI 4140 steel and AISI 1050 steel using friction welding process.

Sunay *et al* (2009) examined friction welding AISI 1050 and AISI 304 steels. They determined the optimum welding parameters as 14 s (friction time), 1.7 MPa (friction pressure), and 2.5 MPa (forging pressure) and 10 s (friction time), 1.2 MPa (friction pressure), and 2.5 MPa (forging pressure), respectively.

Figure 15. Grain flattening of B5 sample in HAZ of 1-4871 material ($\times 450$).

Figure 17. SEM image of 1-4718 material microstructure in distance zone from welding ($\times 4000$).

Figure 16. SEM image of 1-4871 material microstructure in distance zone from welding ($\times 4000$).

Figure 18. SEM image of welding interface in two materials ($\times 4000$).

3.2 Microstructure properties

When microstructure results are examined, it has been observed that friction time does not cause any noticeable differences at inner microstructure due to low friction pressure in group A samples. Heat affected zone (HAZ) was observed to be thicker in group C samples. These zones were seen to be much wider especially in the groups of increasing forging pressure and friction time. Mechanical orientation and wider HAZ are observed on group C5 and 1-4871 materials (figure 13). Mechanical orientation of grains is certainly seen from central to outer parts on grains (figure 14). Certain microstructure and standard thickness HAZ were observed on group B samples.

When forging pressure results are examined, in the inner structure of groups the high forging pressure values from central to outer mechanical orientation in grains, coming out due to deformation during welding, is observed (figure 14). This orientation is possible for each of the two materials. Standard thickness and more obvious HAZ are seen in group B samples (figure 15).

When tensile and notch impact tests results are examined, better mechanical orientation were obtained in group B5 samples as compared with other groups. When optical microscope images of group B5 are examined, martensitic microstructure of 1-4718 materials was present at a distant zone of welding (figure 16). Austenitic microstructure of 1-4871 materials is seen at a zone away from welding (figure 17). HAZ image of A5 sample at centre is shown in figure 18. Black zones occurred in microstructures are Fe₂C carburs on austenit grain boundaries and some austenit grains. HAZ and mechanical orientation and Fe₂C carburs in 1-4871 materials becoming denser along with these orientation lines are seen in figure 19. However, grain shrinking and flatness are clearly observed towards welding line in microstructures on HAZ of B5 samples (figure 20). This grain flatness is shown by higher magnification in figure 21. Grain flattening takes place as orientation of grains in vertical position to the deformation during welding. These microstructures are shown as 1000 times magnified in figure 2, and 4000 times in figure 23. SEM image of 1-4718 materials microstructure in a zone away from welding is shown as 4000 times magnified in figure 24. SEM image of welding interface in two materials is shown as 4000 times magnified in figure 25.

Şahin (2005, 2007), Ateş *et al* (2007), Özdemir (2005) and Özdemir *et al* (2007) and Satyanarayana *et al* (2005) observed thin-grained structure in welding zone, and observed grain orientation on HAZ in medium carbon steels, and stainless steels. Ateş *et al* (2007) reported that HAZ and grain orientation in microstructure increased with increasing friction pressure. They reported that HAZ and grain orientation in microstructure decreased with increasing forging pressure. In our study, similar microstructure results were obtained.

Çelik and Ersözlü (2009) observed no cracks or blank spaces in optical and SEM tests. Grain size reduction occurred at the HAZs of both base materials. It was observed that transition of materials at the welding zone occurred in SEM and EDS analyses. Sunay *et al* (2009) observed that a recrystallized region was formed at the joints produced under long friction time and high friction pressure for both cast and forged parts.

4. Conclusions

In this study, the optimum welding parameters were determined in materials during the joining of X53CrMn NiN219 and X45CrSi93 steels by friction welding. Based on the findings of this research, the following conclusions can be drawn:

- (I) Efficient length shortening quantities cannot be obtained in the samples in which friction time is applied as 2.7 s. It has been determined that there has been more material losses with increased friction pressure and forging pressure in the groups where the highest friction time was 4.7 s. While the ideal length shortening is 7–10 mm, it is 8.85 mm for B5.
- (II) Breaking from welding zone is not observed on the samples of group B5 on tensile tests. For tensile properties, B5 parameter group has been determined as an ideal parameters group.
- (III) The highest fracture energy (toughness) on tensile tests was observed in group B5.
- (IV) Profile hardness of A group occurred on near 1-4871 material of welding zone, and the highest value of hardness of these samples occurred near 1-4718 material of welding zone. The slope of hardness profile on group B and C was much higher than that of group A in the welding zone.
- (V) Carbur formations were clearly observed along direction lines of HAZ and mechanical orientations on optical microscope images of group B5. Austenitic structure occurred on microstructure distant from welding zone 1-4718 and martensitic structure occurred on 1-4871 material at distant welding zone. Next to welding zone, grain shortening and grain flatness occurred as perpendicular deformation in 1-4871 materials.
- (VI) Optimum welding parameters: friction time (t_1) was determined as 3.7 s, friction pressure (P_1) was determined as 207 MPa, forging pressure (P_2) was determined as 414 MPa at B5 group of friction welding of 1-4871 and 1-4718 materials.

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